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We present experimental results of a version of the Choppertron microwave generator designed to work with the high emittance beam of the Advanced Test Accelerator (ATA). Simulations showed that a 800-A, 120 π cm-mrad beam (typical of ATA), could produce 800 MW of rf (11.4 GHz) power using two 12-cell, traveling-wave output structures. Funding contraints prevented final tuning of the modulator system and limited the experiment to 530 MW in narrow pulses. Over 400 MW were extracted from a single output structure through fundamental waveguide. Beam breakup was successfully suppressed with >800 amperes of current transported through the extraction section.

1. INTRODUCTION

We have performed a series of experiments over the past several years to study the application of induction accelerator technology to rf power production for a linear collider in the Two-Beam Accelerator concept. [1,2] Areas of study included high-power (several hundred megawatts at 11.4 GHz) output structures, multiple output structures, transverse beam instabilities caused by excitation of higher order modes (HOM), phase coherency, amplitude stability, and the acceleration of a modulated beam. The Choppertron II completed our microwave experiments at the ATA facility and was designed primarily to expand the limits of peak power extraction and suppression of HOMs.

Figure 1 is a schematic of the Choppertron II. The modulator section has a multi-cavity deflection structure and two off-axis apertures. A schematic of the deflection structure is shown in Fig. 2. The modulator operates by deflecting the beam in the horizontal plane with the 5.7 GHz deflectiion structure. This causes the B_z-field-immersed beam to describe semi-helical trajectories that scan across a pair of off-axis apertures in a collimator located between the drive cavity and the rf output structures. The 5.7 GHz spatially modulated dc beam incident on the collimator is transformed into a phase coherent, amplitude modulated beam at 11.4 GHz. The axial magnetic field is matched to the beam's energy and emittance to keep the desired beam radius and betatron wavelength for efficient operation. The output section has two 12-cell traveling-wave structures. Each has de-Q-ing circuits built into the first two cells to extract power from the HOMs, and a damping cavity after the output coupler.

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II. EXPERIMENTAL LAYOUT

A schematic of the experiment is shown in Fig. 3 The injector is operated at ~ 2.1 MV producing a 6-kA, 80-ns fwhm, current pulse. A 2-cm aperture, 1-m long collimator immersed in a solenoidal field reduces the current to 1-kA and removes low energy electrons from the front/back of the pulse (effective fwhm < 50 ns). The beam energy is increased to 4.6 MeV with 10 ATA induction cells. The beam is deflected upon entering the Choppertron modulator section and swept back and forth across the two apertures. This reduces the dc current by about half, but produces a well modulated beam. A dc deflection magnet located around the deflection structure is used to assist with initial magnet settings. The solenoidal field is increased at the entrance of the rf output section to limit the beam motion to within the 16-mm aperture of the output structures.

The dc current component is measured with resistive wall current monitors before and after the Choppertron. RF loops inserted in a safety collimator in front of the deflection structure measures the current entering the structure. Resistive dividers on the induction modules are used to determine gap voltage and infer beam energy. The dc deflection magnet also functions as an energy spectrometer. The amplitude and frequency of the rf power entering and exiting the deflection structure is monitored. The output power pulses are sampled with 56 db directional couplers and measured using Schottky diode detectors. Phase coherency and power spectra of the pulses is also measured.

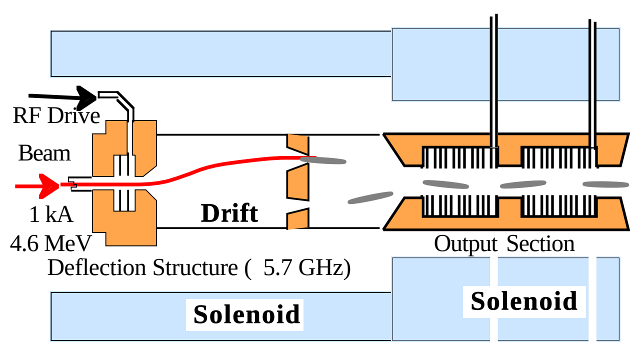

Figure 1. Schematic of Choppertron II.

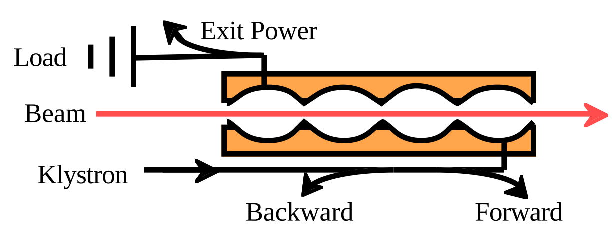

Figure 2. Schematic of the deflection structure.

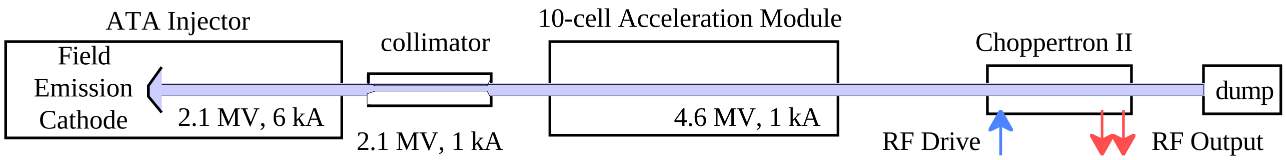

Figure 3. Schematic of the experimental layout.

III. EXPERIMENTAL RESULTS

A. Deflection Cavity Measurements

The original Choppertron [3] had been designed for a 30 π cm-mrad beam that could have been produced with an induction accelerator using a dispenser cathode. To accommodate the ATA beam, modifications were made to the modulator that required increasing the solenoidal field and shortening of the drift distance. A significant increase of the rf deflection fields was also needed. The new deflection structure requires about 2 MW of forward rf power at 5.7 GHz. The rf energy stored in a TM_{110}-like resonant mode deflects the beam as it passes through the structure. The beam then drives the resonant mode increasing the deflecting fields to the desired level.

A bi-directional coupler was used to measure forward and backward propagating power with respect to the deflection structure input port. The observed backward propagating power from the input port, with and without beam, is shown in Fig. 4. The drive power pulse started about 200 ns prior to the ≈50 ns beam pulse to allow for transients. The effect of beam loading is obvious.

A desired characteristic of the deflection system is that the beam-generated power be proportional to the drive power. The peak reflected power from the input port for two different beam loadings as a function of drive power is shown in Fig. 5. A major difficulty is avoiding other resonance's and adjusting the beam loaded frequency of the desired resonance. The spectrum analysis of the power generated in the deflection structure by the beam indicated a resonant frequency of 5.703 GHz. This is the cutoff frequency for the coupling port.

B. Output Power Pulses

Low power conditioning of the Choppertron, at output power levels of 10 to 20 MW, was accomplished using beam currents below 200 A. As the current is increased, the shape of the output power pulses, and transmitted current pulse measured at the beam dump, changed. Figure 6 shows typical pulses from the first output structure for several different currents. The second output and transmitted current pulses had similar shapes. No evidence of electrical breakdown or transverse instability was noted in the output structures to explain the shortening of the pulses.

At higher currents (> 300 A), the driving frequency of the deflection structure effected the output pulse shape. Figure 7 shows typical pulses from the second output structure at different drive frequencies. Maximum power levels occurred at a drive frequency of 5.709 GHz, dropping rapidly with lower, and gradually with higher, frequencies. Pulse shape variation occurred for different currents and magnetic transport, but the trend is consistent with Fig. 7, i.e. the peak power would occur later with respect to the current pulse with increased frequency. The pulse from the first output did not display the notch shown for the 5.709 GHz pulse in Fig. 7.

Below drive frequencies of 5.718 GHz, up to twice the power could be extracted from the first structure than from the second. Above 5.720 GHz, about equal powers were extracted. Maximum powers measured were 420 MW for

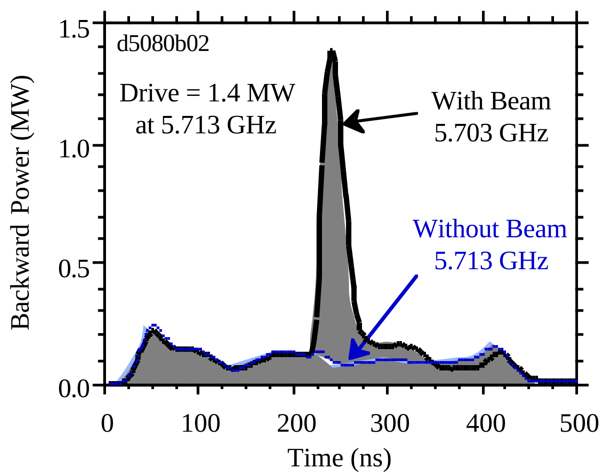

Figure 4. Backward power from the deflection structure indicated substantial power was generated by beam loading.

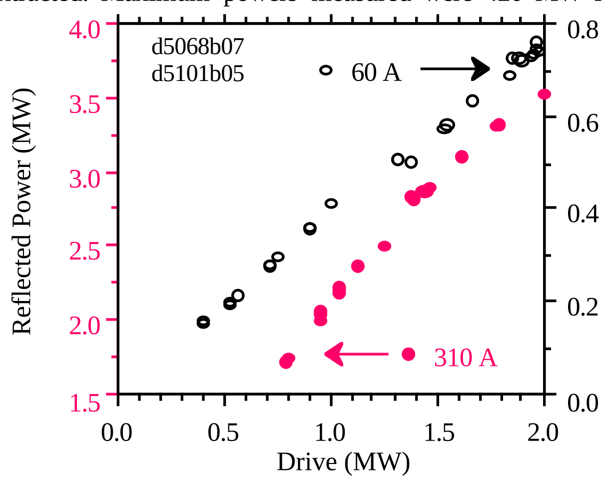

Figure 5. Power generated by beam loading in the deflection structure varied linearly with drive power.

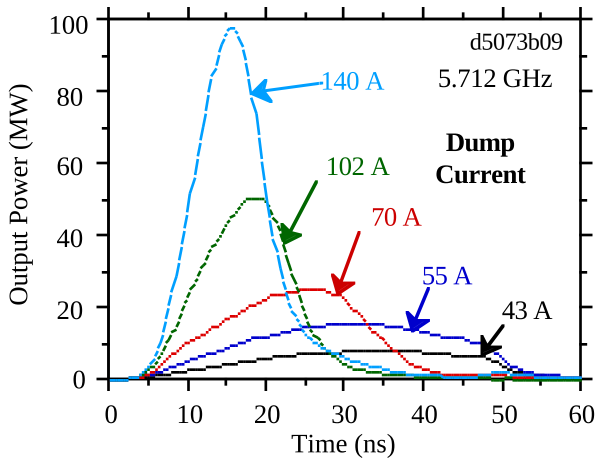

Figure 6. Power pulses from the first output structure.

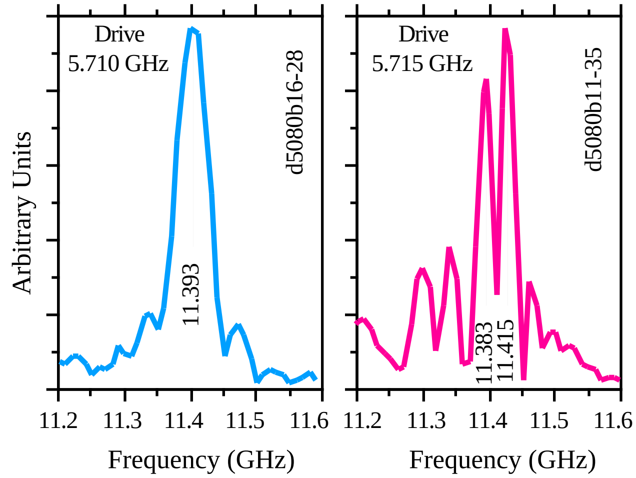

Figure 8. Power spectra of rf output pulses.

the first and 260 MW for the second. Combined totals of over 500 MW, e.g. 379 + 151 = 530 and 285 + 231 = 516, were obtained. These powers were associated with pulse shapes similar to the narrower pulses shown in Fig. 6 and 7.

C. Frequency Analysis

Power spectra were made of rf pulses related to the deflection structure and output power structures. Initial measurements on the deflection structure indicated resonant peaks during beam loading at 5.689 and 5.722 GHz (drive frequency = 5.714 GHz). After tuning, resonant peaks were measured with beam at 5.703 and 5.713 GHz (drive frequency = 5.713 GHz). Typical spectra for pulses from each of the output structures are shown in Fig. 8. At lower drive frequencies, the output power is primarily at 11.393 GHz. Increasing the drive frequency leads to the power being split in two frequency components.

D. Comments on Transverse Instabilities

Over 800 A was transported through Choppertron II using the dc deflector magnet with no indication of beam disruption due to transverse instabilities. This is an important accomplishment due to the number of cells involved

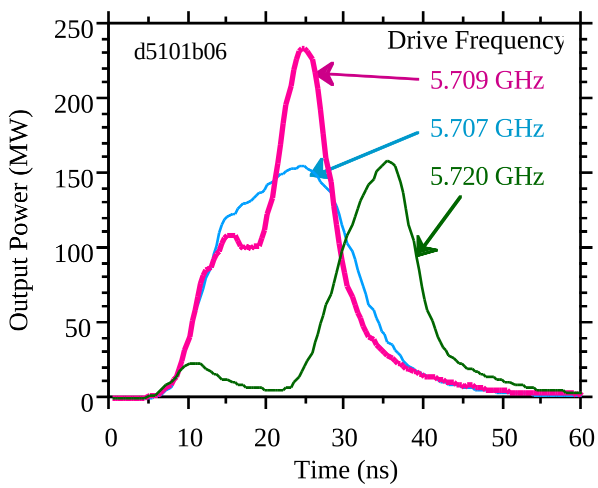

Figure 7. Power pulses from the second output structure.

the fact that the two output structures are identical, and that the beam is deflected off-axis prior to the output section.

IV. CONCLUSIONS

Extracting 420 MW from a single output structure into fundamental waveguide nearly doubled the power level achieved with the original Choppertron and the same output structure. [2] This peak power increase is attributed to improve vacuum conditions and increased rf current due to the new modulator. While high peak powers were attained, the pulses were narrow and we had difficulties with mode purity at higher drive frequencies. Several corrective actions are possible, e.g. decreasing the separation of the off-axis apertures to reduce the necessary beam deflection and lessen excitation of unwanted resonances, and additional tuning of the deflection structure to reduce the strength of unwanted resonances. Tuning of the deflection structure after initial testing substantially reduced the effect of these resonances in the final experiment. Unfortunately, we are unable to perform further experiments due to funding constraints. The output structures may be used in future experiments on relativistic klystrons. [4]

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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